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MULTIANGULAR SCANNING ABSORPTION-EMISSION TECHNIQUES FOR THREE --ETC(U)
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MULTIANGULAR SCANNING ABSORPTION-EMISSION TECHNIQUES FOR THREE DIMENSIONAL COMBUSTION DIAGNOSTICS

AFOSR 77-3439
Annual Technical Report

prepared for:

AFOSR, Bolling AFB

Attn: Dr. B.T. Wolfson

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The George Washington University
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TECHNICAL OBJECTIVES

As better measurement techniques become available, new ranges of combustion phenomena can be studied with the accuracy necessary for meaningful interpretation. In particular, the potential of optical methods as compared to that of classical probes should be evaluated in the context of the phenomenology needed for the design of current and future combustors. Specifically, it is proposed to extend the absorption-emission methods previcusly limited to one-dimensional and axisymmetrical flows ("onion-peeling"), to the more realistic 3-dimensional flow fields found in actual combustion devices.

The relevance of such a study to the research needs of the Air Force is supported by the constant need expressed in propulsion design groups, for a combustion phenomenology verified realistically by accurate diagnostics. Since current measurement techniques are for the most part constrained to point measurements with little flexibility for the recording of time- or space- histories (i.e., correlations or profiles), the proposed technique would answer a serious need in real, 3-dimensional and often unsteady systems.

CURRENT STATUS

a. Typical pollutant/radical distribution in flames have been simulated by summation of Gaussian curves and also by uniform areas of concentration inside a flame cross section.

b. Two distinct multiangular algorithms are being tested on these synthetic profiles: one based on two-dimensional Fourier transforms, the other on an iteration (back-projection) method. Work is proceeding satisfactorily, with some partial results available. It is reviewed in Part II of this technical report. Substantial support (mostly advice) has been given by the Washington medical research community (X-Ray Tomography) and by interferometry specialists (Dr. Sweeney).

c. As we move towards a practical design for pollution/radical diagnostics by the end of this grant, we have also explored the use of multiangular techniques in X-Ray applications. Following a visit to Dr. McGregor at AFRPL (January 1978), several applications of X-Ray techniques to Air Force needs have been evaluated (a report co-authored by Dr. Geskin is in preparation).

d. A continuing assessment is being made of the various competing diagnostics techniques susceptible of application in Air Force present programs and future research plans, especially in air breathing propulsion. In this very active field, expectations and risks are difficult to assess, especially when novel techniques (CARS, fluorescence) are proposed. A review paper is being prepared.

e. Three seminars on this current work have been given in the last 8 months (Howard U., NASA-Langley and AFRPL). A paper was presented

at the 1978 Central State Section Meeting of the Combustion Institute. A review of the absorption diagnostics has been prepared for the AIAA Aerospace Sciences meeting in January 1979 (Paper 79-0085).

f. The personnel involved in this research have been:

R. Goulard, principal investigator (3 man-months)

E. Geskin (1½ man-months)

P. Emmerman (2 man-months)

ABSORPTION TECHNIQUES IN 3-DIMENSIONAL DIAGNOSTICS

In three dimensional diagnostics of concentrations and temperature, point measurement techniques, such as Raman scattering for instance, suffer from very small cross sections and are therefore limited in their threshold and accuracy. Path measurement techniques (interferometry, absorption) correspond to much larger cross sections and are therefore more accurate. However, these measurements are path-integrated and it is necessary to treat them by suitable mathematical algorithms in order to obtain properties at every point in the medium.

There exists (Goulard 1976) two ways to generate the information necessary to obtain the profile of a property along a line (n points) or for a planar cross section ($m \times n$ grid). One is frequency-scanning where n frequencies are measured along a given line of sight. This method has been evolved with great success in satellite meteorology and stellar atmospheres (Wark et al. 1966, Chahine 1970, Jeffries 1968). The other is multiangular scanning where the absorption of m equally-spaced parallel beams is measured in a given direction Θ (m measurements); the procedure is then repeated for n other angles (see Fig. 1). From the resulting set of $m \times n$ data, it is possible to retrieve a $m \times n$ grid of properties.

The frequency-scanning method has been used in the case of combustion (Chao and Goulard, 1974), but the inherent difficulty of converting optical lengths (i.e., density × length) to physical lengths, makes it cumbersome, except for those cases where additional information is available (e.g. known mixing ratio, density law, etc. (Goulard, 1977a)). The multiangular method has been applied to interferometry (Sweeney and Vest 1974) and X-Ray diagnostics (the latter with great commercial success (Brooks and diChiro, 1976; Gordon et al., 1975)). The procedure is outlined below.

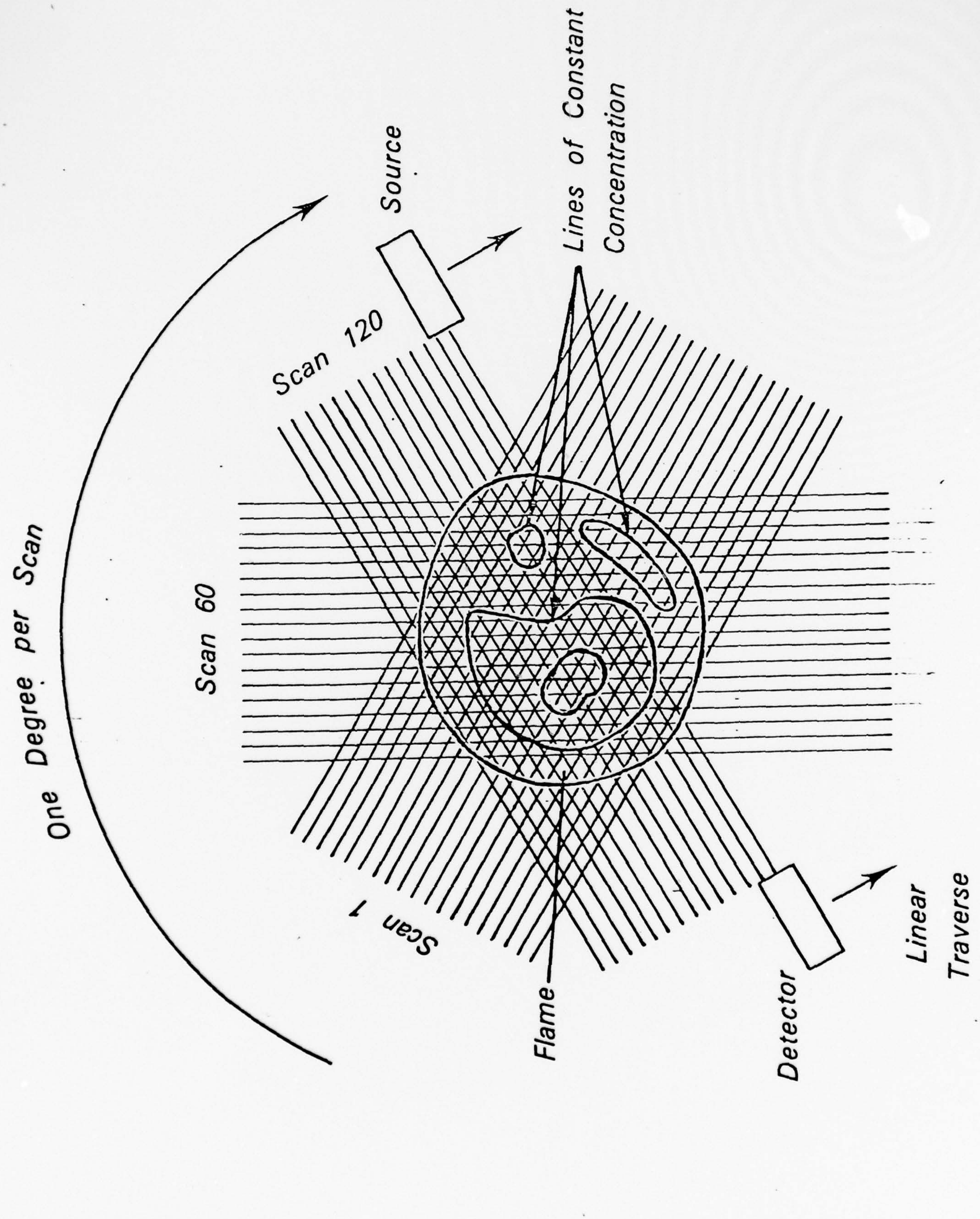


Fig. 1. Typical Scanner. 180 values of θ are used and 160 parallel beams for each value of θ (Delta Scanner, Ohio Nuclear, Inc.).

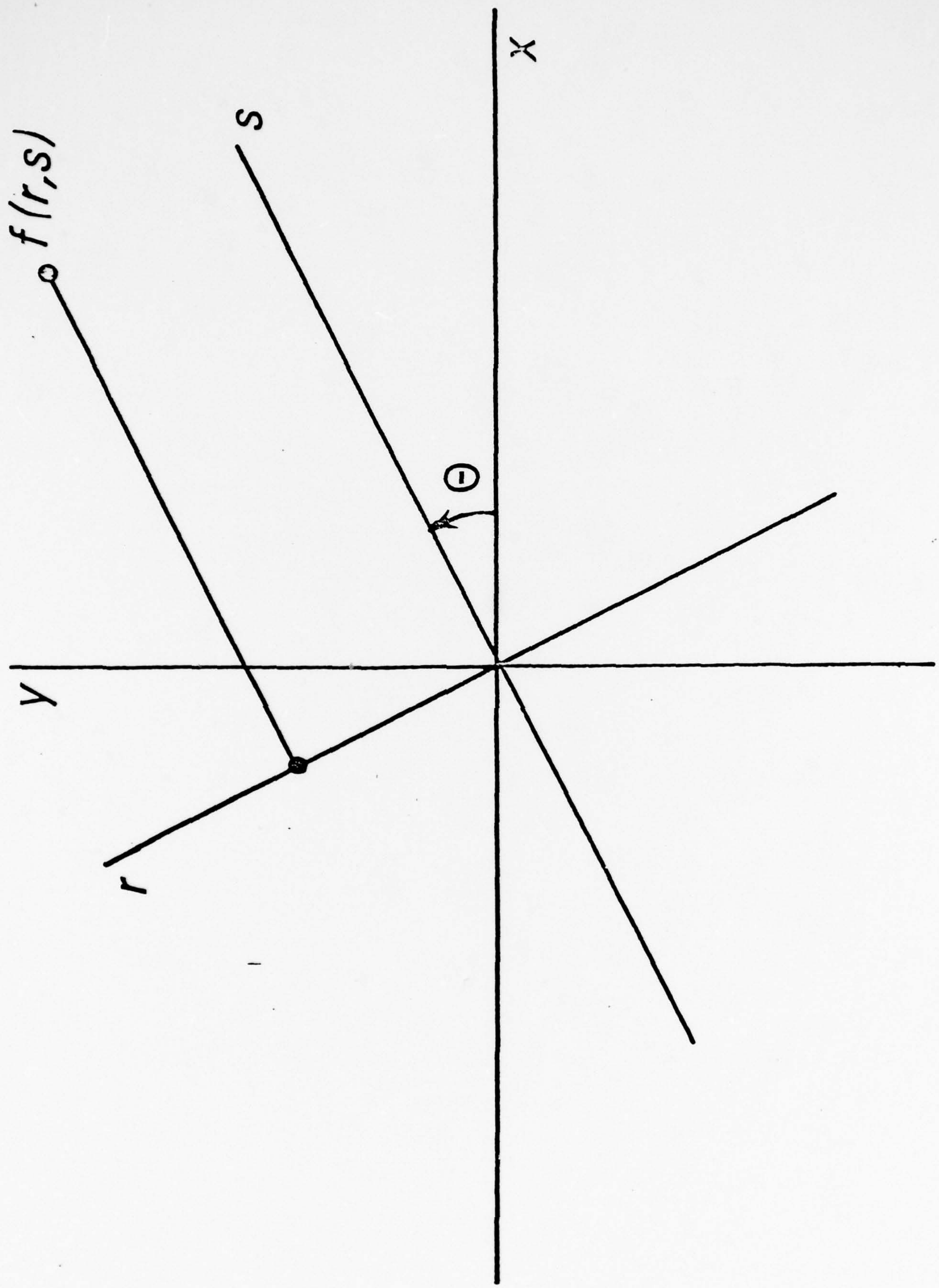


Fig. 2. Cartesian and Scanning Coordinates.

The Multiangular Scanning Procedure

The multiangular scanning technique is based (Fig. 2) on the image reconstruction of a property field f(x,y) from its projection in the Θ direction:

$$f_{\Theta}(r) = \int_{-\infty}^{+\infty} f(r,s)\, ds \qquad (1)$$

where: $r = x \cos \Theta + y \sin \Theta$

$s = -x \sin \Theta + y \cos \Theta$

There exists a number of mathematical methods which use the set of (m × n) values of $f_{\Theta}(r)$ obtained experimentally (by scanning the field of interest for m values of Θ and n values of r), and then convert this data into a (m × n) grid of f(x,y) values. At the limit, an infinite number of measurements would give an exact map of f(x,y). Once the map f(x,y) has been established for a section z, measurements are performed at other sections z and eventually the three dimensional map f(x,y,z) is obtained.

In the case of flame absorption data, if a beam of initial intensity I_o emerges from the flame with an intensity I, the absorption equation takes the form:

$$\frac{I}{I_o} = \exp\left[-\int_{-\infty}^{+\infty} (N_i Q_i ds)\right] \qquad (2)$$

where the product (cross section Q_i x concentration N_i) for the component i can be considered as a local function f(r,s) of the thermodynamic properties and concentration of i at the point (r,s) or (x,y). Since the ratio I/I_o can be measured experimentally, it is seen that by writing Eq. 2 in the form

$$-\log \frac{I}{I_o} = \int_{-\infty}^{+\infty} (N_i Q_i)\, ds \quad , \qquad (3)$$

the techniques developed in other fields of application to solve Eq. 1 can be readily extended to the 3-dimensional measurement of $(N_i Q_i)$ in flames.

If this measurement is made at the frequencies of two excited states of the same band, the ratio of the two retrieved values yields the temperature T through a Bolzmann relationship (see Chen and Goulard 1976). The knowledge of the (x,y) maps of $N_i Q_i$ and T yields in turn the concentration N_i, since Q_i is available from the literature as a function of T.

In practice, except for the "generalized onion peeling" method proposed by Chen et al (1976), the multiple angular scanning method has not been applied to absorption. However, it has been used successfully in interferometry and X-Ray tomography. Since "onion peeling" methods amplify experimental errors, the available algorithms developed for interferometry and tomography are worth closer inspection in terms of possible use in absorption experiments. They fall in three general categories which have been evaluated and compared, especially in both contexts of X-Ray tomography (Brooks and diChiro 1976) and interferometry (Sweeney and Vest 1974, Radulovic and Vest 1976).

1. Two-dimensional Fourier transforms. This method is based on the fact that by taking the Fourier transform of Eq. 1, one obtains a "spectrum" $F_\Theta(\rho)$ of the experimentally available function $f_\Theta(r)$:

$$F_\Theta(\rho) \equiv \int_{-\infty}^{+\infty} f_\Theta(r) e^{-2\pi i \rho r}\, dr,$$

where ρ is an integer which can take any number of values: 1,2,... It is possible also to construct a function (Θ,ρ):

$$\mathcal{F}(\Theta,\rho) \equiv \int_{-\infty}^{+\infty} F_\Theta(\rho) e^{-2\pi i \Theta s}\, ds,$$

where Θ is another integer, which in this application is the measurement

angle θ. The function $\mathcal{F}$ can be written then:

$$\mathcal{F}(\Theta,\rho) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(r,s)e^{-2\pi i(\rho r + \Theta s)}\,drds \qquad (4)$$

which is clearly a two-dimensional Fourier transform of the function f. Therefore, its inverse Fourier transform is the unknown function f. Numerical methods, using finite series rather than integrals, have been adapted to this case. Their accuracy improves with the number of measurements and they tend to be successful mostly for situations where access is free from all angles.

However, it should be noted that Fourier transform calculations can be initiated only after <u>all</u> the data (Θ) has been collected (Eq. 4). <u>Fast Fourier Transform</u> techniques (FFT) have accelerated this process substantially (Bendat 1971, Thomson 1976), but still faster procedures have been evolved. In the <u>convolution methods</u> developed by Ramachandran (1974), the profiles $f_\Theta(r)$ collected for each Θ are *immediately "back projected"* on the beam (Θ,r). The picture matrix is thus constructed in cumulative fashion as the angular scanning proceeds over Θ. Typically (Ledley 1976), an ACTA-scanner will deliver a 64,000 element map of (N_iQ_i) in 4½ minutes or less. This method has been extremely successful in detecting lesions and abnormalities in brain or limb cross sections, based only on the absorption characteristics of such tissues in the X-Ray range.

2. <u>Series expansions</u>. This approach relies on the properties of certain series expansions to match by their first terms the main features of the property profiles. For instance, the Hermitian polynomials $H_{mn}(x,y)$ have been shown to be well suited to near-Gaussian density profiles by Matulka and Collins (1971).

3. <u>Iterative techniques</u> are based on straight forward algorithms

which repeatedly adjust the estimated f(x,y) map until convergence is accomplished. This is done by comparing for each beam (θ,r), the value of $f_\theta(r)$ calculated on the basis of the estimated vlaues of f(x,y), with the actual measurement of $f_\theta(r)$. An algorithm increases then the estimated f(s,y) values along the beam (r,θ) by the <u>same</u> increment, in such a way as to reduce the difference between measured and calculated $f_\theta(r)$ to zero. The procedure is repeated until the predicted values of $f_\theta(r)$ coincide with actual measurements <u>for all θ's.</u> Obviously, a clever choice of mathematical "filters" is essential to this approach. Often called "Algebraic Reconstruction Techniques (ART)", they have been found to be very successful in a number of early applications, in particular when no a-priori knowledge of the profile existed. Their convergence can be accelerated by smoothing techniques (Chen and Goulard 1976, Baba and Murata 1977). Such methods can handle also highly non-linear cases, as it has been demonstrated in frequency-scanning techniques (Chao and Goulard 1974). However, such methods are "brute force" and convergence can be laborious. Most commercial scanners use a variation of the Fourier transform approach.

APPLICATION TO COMBUSTION PROBLEMS

The applicability of multiangular methods to absorption techniques is tied to the existence of absorption bands which can be matched by existing light sources. Such combinations have been exploited for years by combustion experimentalists. Listed below are typical species found in flames and their absorption cross section Q_i:

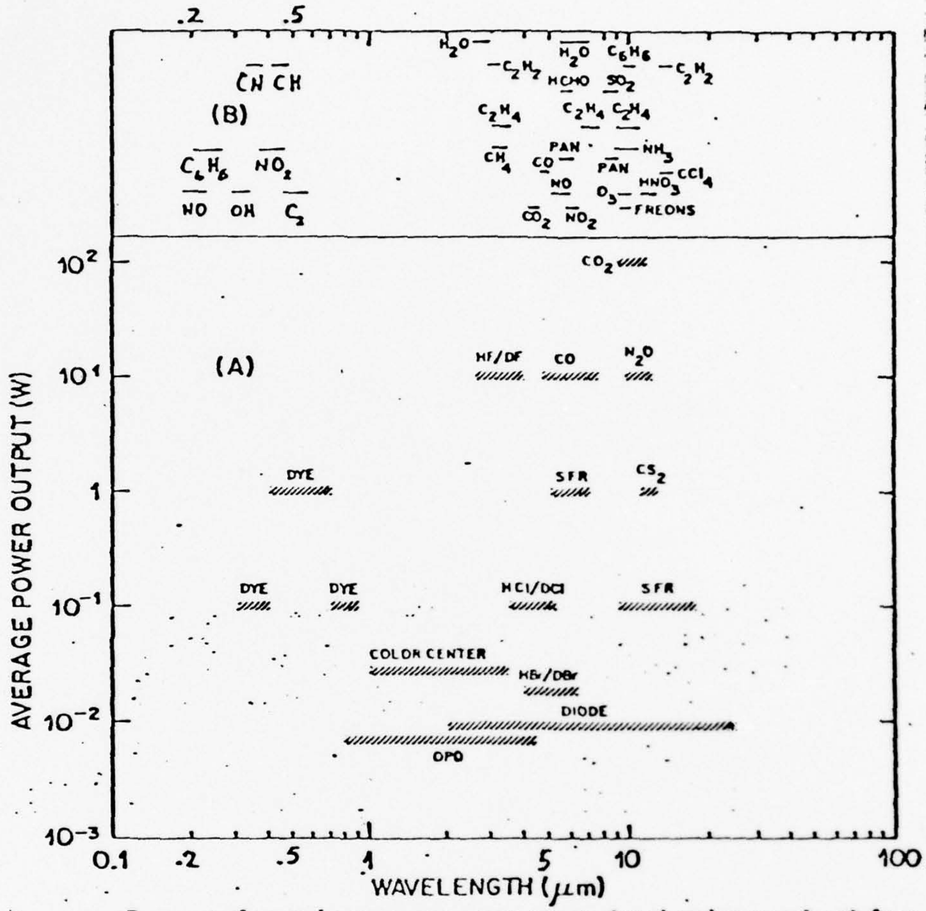
CO	$\lambda = 4.74\ \mu$	$Q_i = 1.7 \times 10^{-18}$ cm^2
NO	$= 0.22$	$= .5 \times 10^{-17}$
C_6H_6	$= 0.25$	$= 1.3 \times 10^{-18}$

OH	$\lambda = 0.31\ \mu$	$Q_i = 5.1 \times 10^{-17}\ cm^2$
NO_2	$= 0.4$	$= 1.1 \times 10^{-17}$
CO_2	$= 4.3$	$= 1.8 \times 10^{-17}$
H_2O	$= 2.7$	$= 6.1 \times 10^{-18}$
SO_2	$= 8.8$	$= 5 \times 10^{-20}$
C_2H_4	$=10.54$	$= 1 \times 10^{-18}$

For samples a few inches deep, the effective detection threshold corresponds to a transmittance which is equal to about 10^{-2} with ordinary light sources (Goulard 1976). However, the advent of tunable lasers (see Fig. 3) combined with differential absorption techniques, have led to thresholds of the order of 10^{-4} (Patel 1978). Therefore, the values of Q_i listed above allow for a concentration threshold of the order of 100 ppm with ordinary sources and 1ppm with laser sources. Hence the great promise of the absorption multiangular scanning method.

In practical combustion systems, a very important question is the kind of optical access which is available to the experimentalist. In interferometry, the effect of the reduction of the view angle from 180° to 90° or to 45° has been evaluated by Sweeney and Vest (1973) from the standpoint of error increase and computer time gains. Similarly, Rachamandran (1971) has estimated the loss of accuracy incurred when the number of viewing angles Θ is reduced to twelve or three. There again, the conclusions seem to depend very much on the particular field and especially on the profiles being measured.

The effect of such constraints on the optimal choice and number of viewing angles would be a critical factor in the design of an absorption diagnostics device for combustion applications. In medical tomography, such devices as fan-shaped beams (see Fig. 4) are an important practical improvement over the basic parallel-beam concept for both standpoints of access and rapid



Summary of approximate average power output plotted against wavelength for a variety of continuously and discretely tunable lasers in the visible and the near infrared region. The output powers denoted on the figure are for typical laboratory-sized lasers. (B) Spectral regions of absorption arising from vibrational-rotational transitions of some typical molecules of interest in pollution detection.

Fig. 3 - Spectral range of radicals, pollutants and tunable laser sources (after Patel 1978). The radicals in the electronic transition range were added.

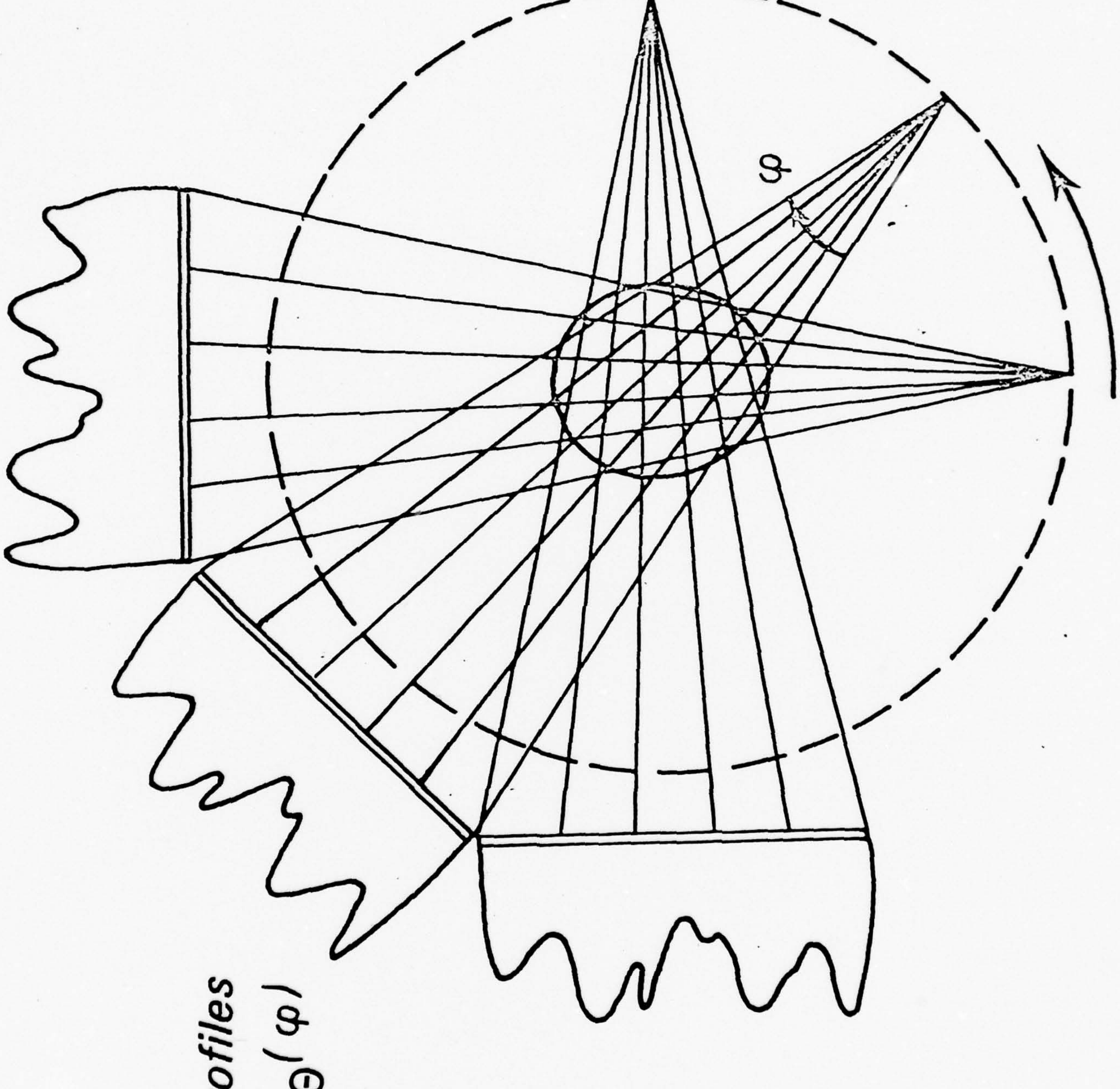


Fig. 4. Fan-Shaped Beams in absorption (ACTA-scanner).

completion.

Finally, the availability of instantaneous 3-D measurements would be a major improvement on current scanning techniques in such applications as turbulent combustion, for instance. A cluster of simultaneously fired sources has been tested in heart tomography (Wood 1977). Also, and less expensively, a single laser source combined with beam-splitting mirrors was used successfully in interferometry (Matulka 1971). It should be investigated for accuracy and resolution in flame mapping.

The purpose of our work is to develop a technique suited to combustion diagnostics. The following section describes our results in exploring optimal algorithms and number of viewing angles. An experimental design is also proposed.

DEVELOPMENT OF THE TECHNIQUE

The search for an optimal 3-D absorption device suitable to flames should emphasize the need for dependable measurements under conditions of limited access and short time response.

A reduction of the number of angles from which measurements are made is a first step towards overcoming access limitation problems. However, the accuracy obtained when many viewing angles are available (180 for instance) is compromised when such a reduction occurs. The theoretical part of this report will describe our search for an acceptable trade-off on the number of viewing angles.

To be able to investigate experimentally the evolution of a combustion process, time resolutions of the order of 20 KHz may be required. Therefore a source illuminating the flame should produce a set of absorption signals to be emitted and collected within 50 microsec. Such a device - assuming five viewing angles, for instance - could be constructed as shown on Fig. 5. The light source could be either a laser beam extended to encompass the full extent of the flame, or else a thin beam which could be made to scan the area of interest by means of a fast piezo electric raster system (60 MHz devices are available). In both cases, continuous recording is possible. The design and construction of this device is being considered by the National Bureau of Standards' Thermal Processes Division, in conjunction with this study.

The determination of the optimum number of viewing angles is the goal of our current theoretical effort. The convolution algorithm was chosen as the primary means to analyze the reconstruction of a variety of symmetric and non-symmetric, continuous and discontinuous functions. This algorithm, which is representative of the class of Fourier based reconstruction techniques,

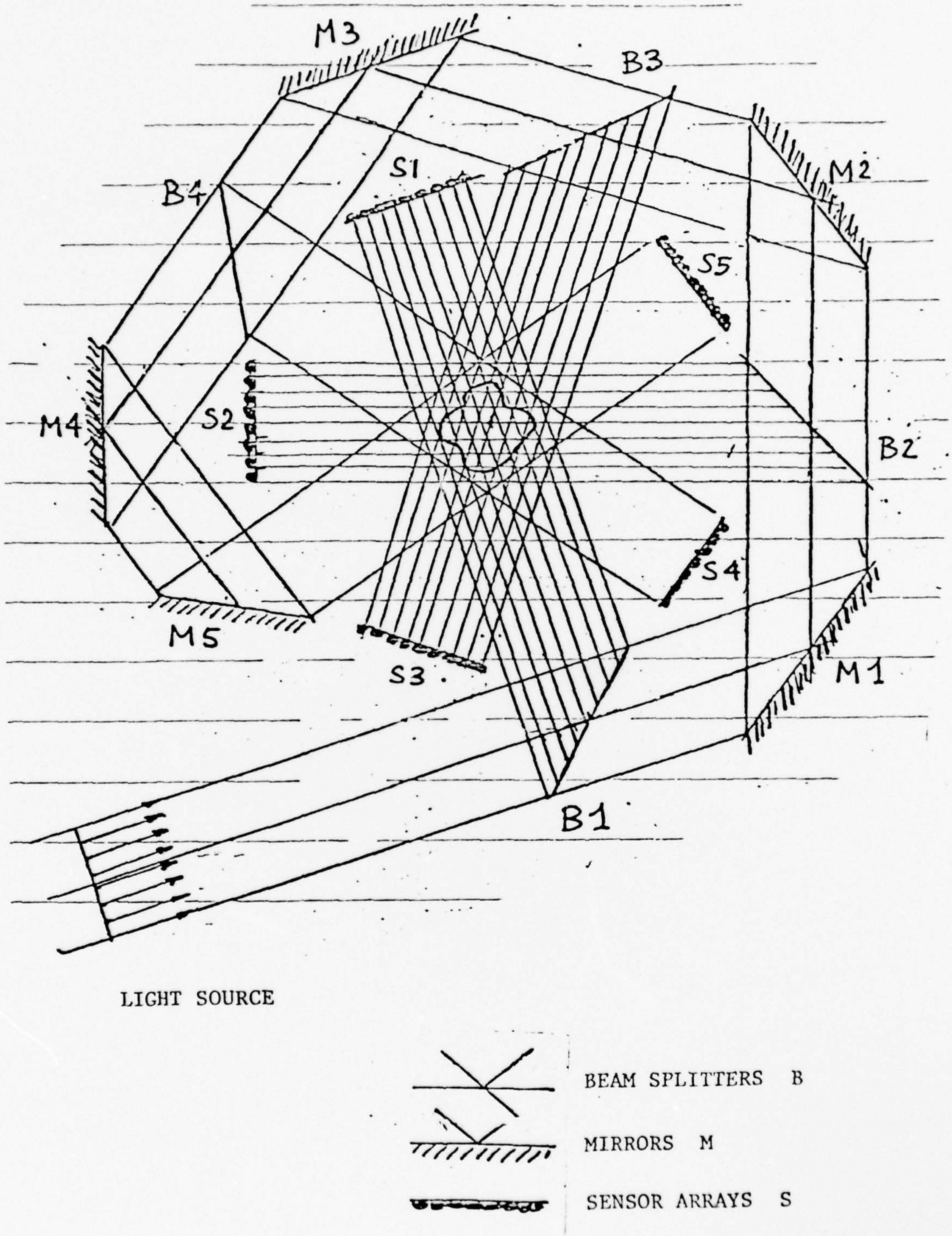


Figure 5 - Instantaneous Multiangular Scanning (5 x 100).

has the advantages of speed of implementation and of being analytically tractable. A comparison is made between the Fourier based algorithms and the iterative algebraic reconstruction techniques. Test functions composed of three dimensional Gaussian fields (Fig. 6) represent the anticipated distribution in an unconstrained combustion process. Constrained combustion processes are approximated by a summation of cylindrical and Gaussian functions.

A rough qualitative evaluation of Gaussian functions can be obtained with as few as three equally spaced functions. To ascertain an accurate reproduction of these functions (error in the order of 1%), ten equally spaced projections are sufficient. If a reconstruction error in the order of 10% (particularly in the periphery of the spatial domain) can be tolerated, as few as six projections are sufficient (Figs. 6,7,8,9). It can be seen that most errors occur at the edge of the flame, where it is easy to substitute our a-priori physical knowledge of field (uniform). Such filtering is common practice in image reconstruction and it is hoped that it will reduce the rms error shown on Fig. 10 to the point where good accuracy will be obtained for five viewing angles only.

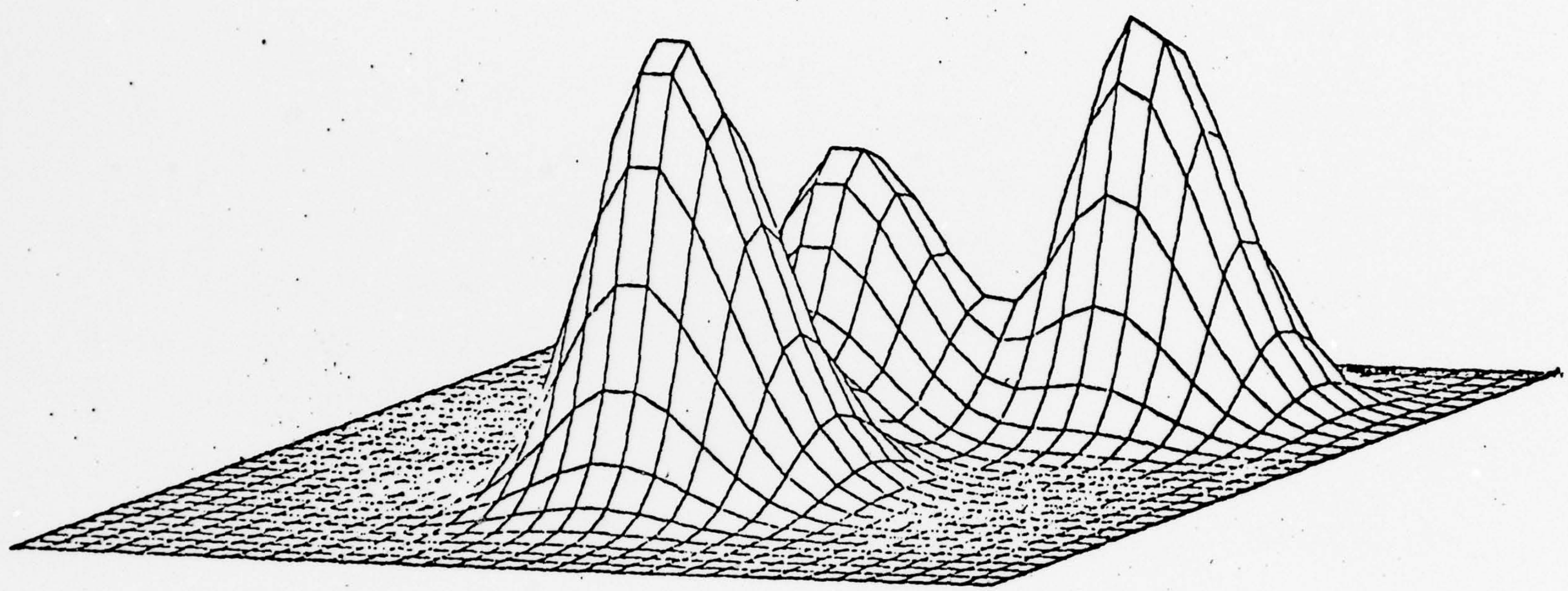
As would be expected, functions which have discontinuities are much more difficult to reconstruct, although proper filtering has a large effect on the accuracy of the reproduction. Small amplitude Gaussian distributions easily become obscured by the ringing caused by these discontinuities (Figs. 11 and 12). To be able to limit the number of projections necessary for a reasonably accurate reconstruction, significant preprocessing of the data shall be required.

CONCLUSION

Therefore, in terms of practical flame applications, there seem to be two areas of useful absorption diagnostics. One is for three-dimensional real time measurements of low concentrations from a laser-beam splitters-sensors combination, operating from a few viewing angles. This will be satisfactory provided the profiles are relatively smooth (e.g. a set of Gaussians (Fig. 6), or at least representable by a model depending on a few parameters only). Many flames correspond to this description.

The other is for three-dimensional measurements of arbitrarily complicated and discontinuous maps of low concentrations. Such applications require many viewing angles (Fig. 11). If such open access is available (e.g. in X-Ray applications), extremely fine resolution is expected, as has been demonstrated in medical and material testing tomography. It does require, however, expensive multiple sources or,(more cheaply), the time-averaging of sequential measurements. Solid propellants, fluidized beds, etc... could be investigated in that fashion.

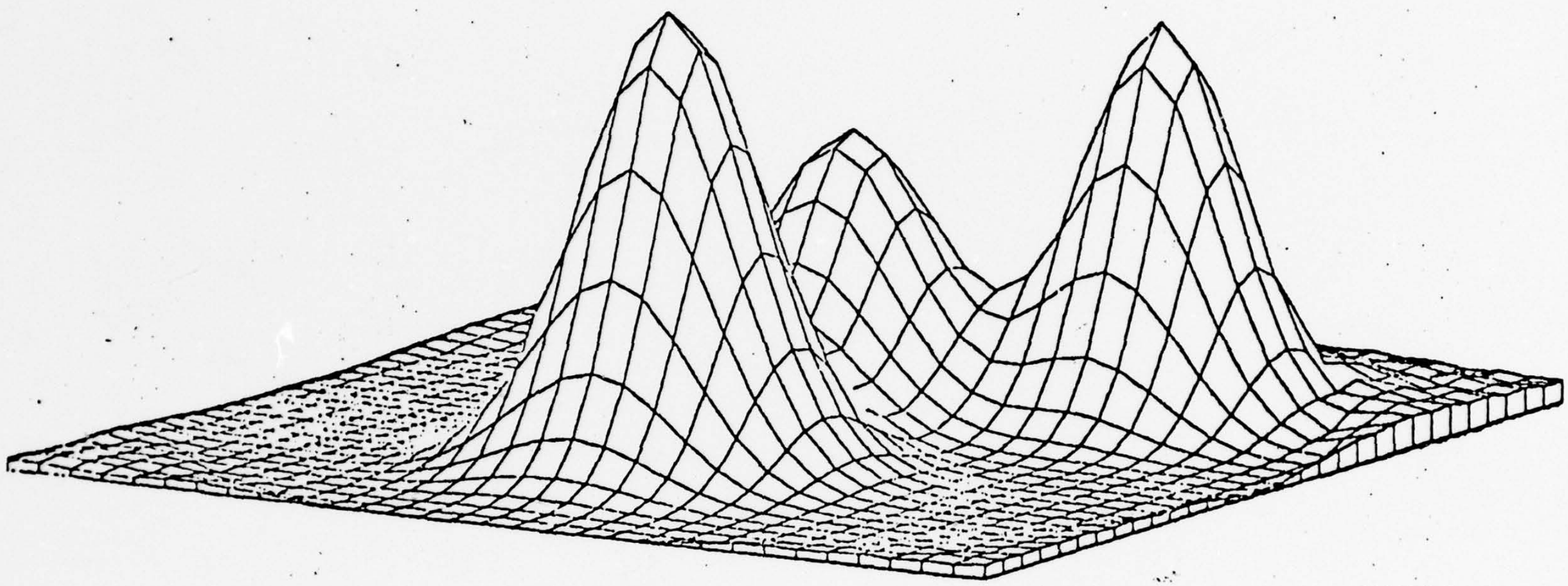
SUMMATION OF GAUSSIAN DISTRIBUTIONS



TRUE FUNCTION

Figure 6

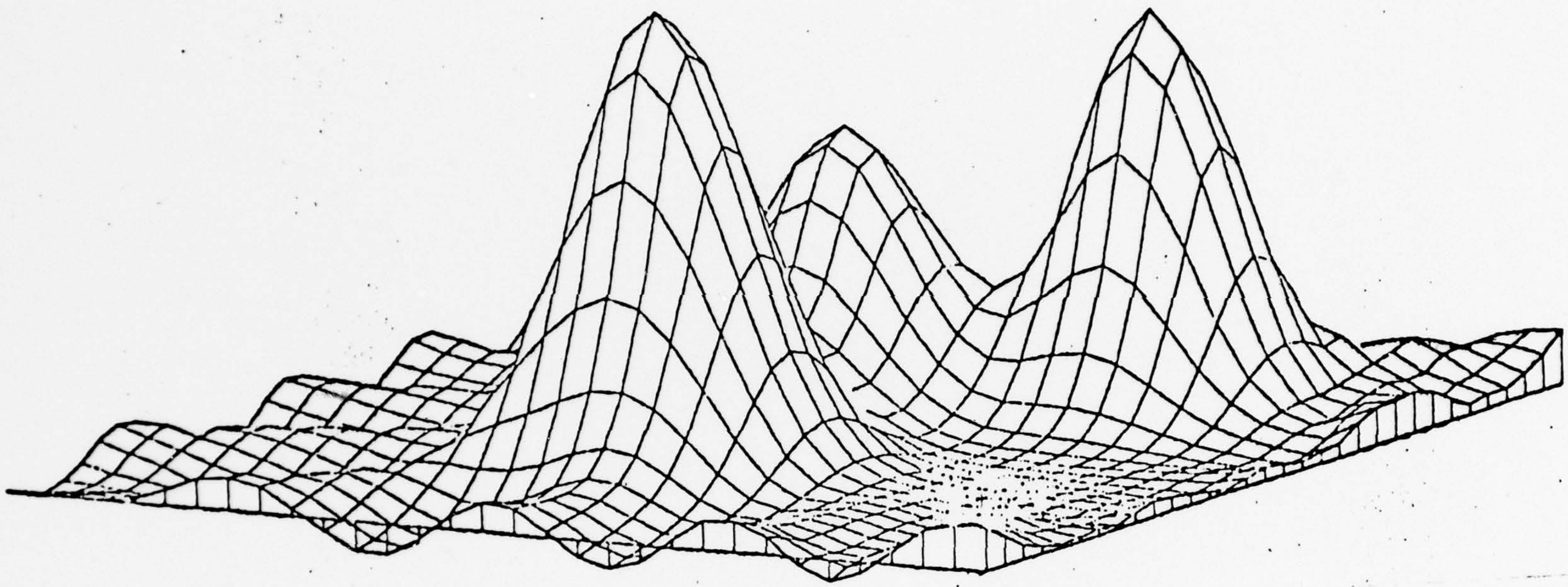
SUMMATION OF GAUSSIAN DISTRIBUTIONS



20 SCANS

Figure 7

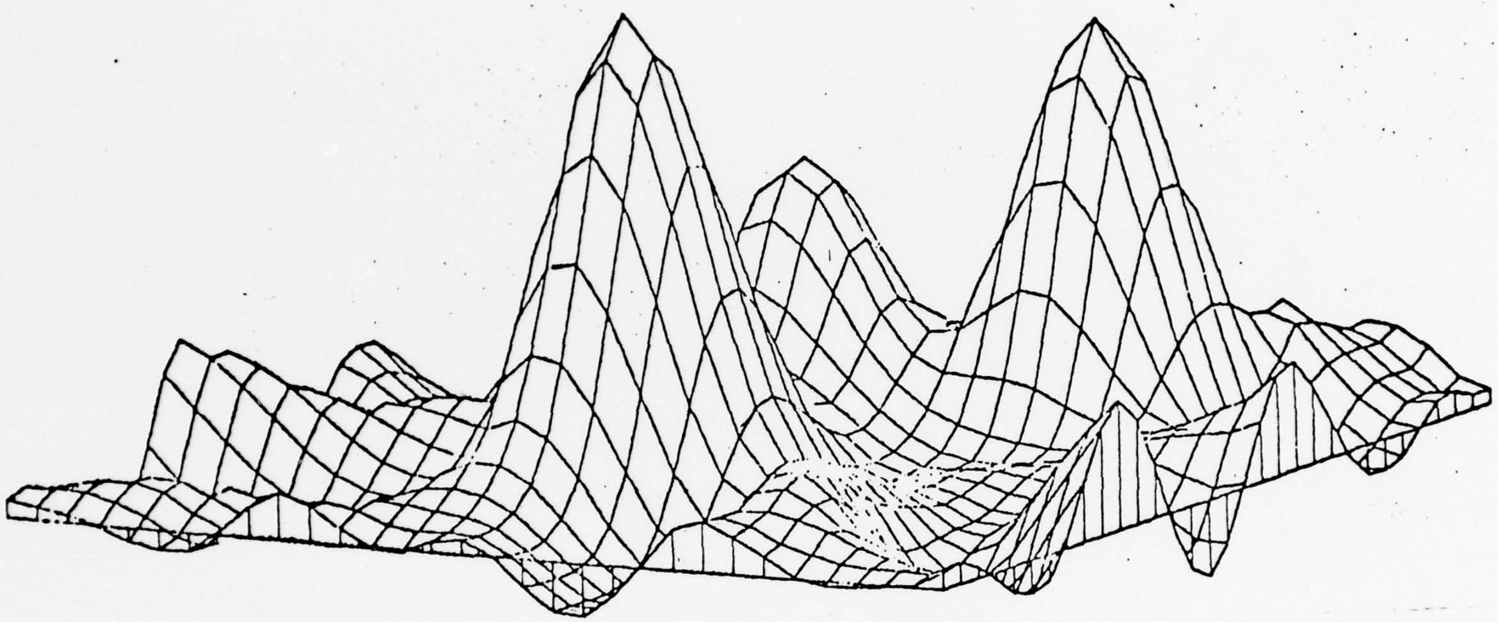
SUMMATION OF GAUSSIAN DISTRIBUTIONS



10 SCANS

Figure 8

SUMMATION OF GAUSSIAN DISTRIBUTIONS



6 SCANS

Figure 9

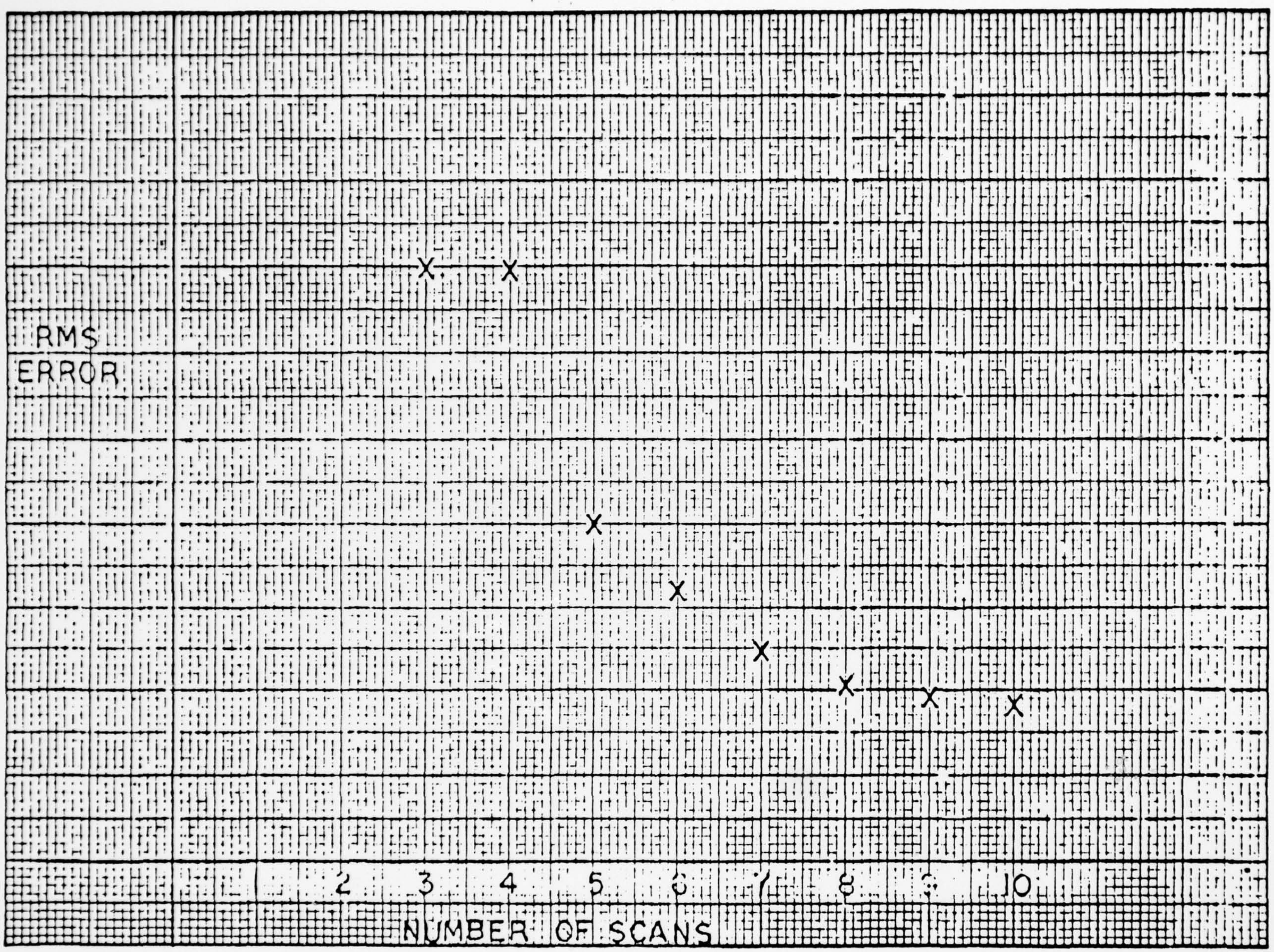
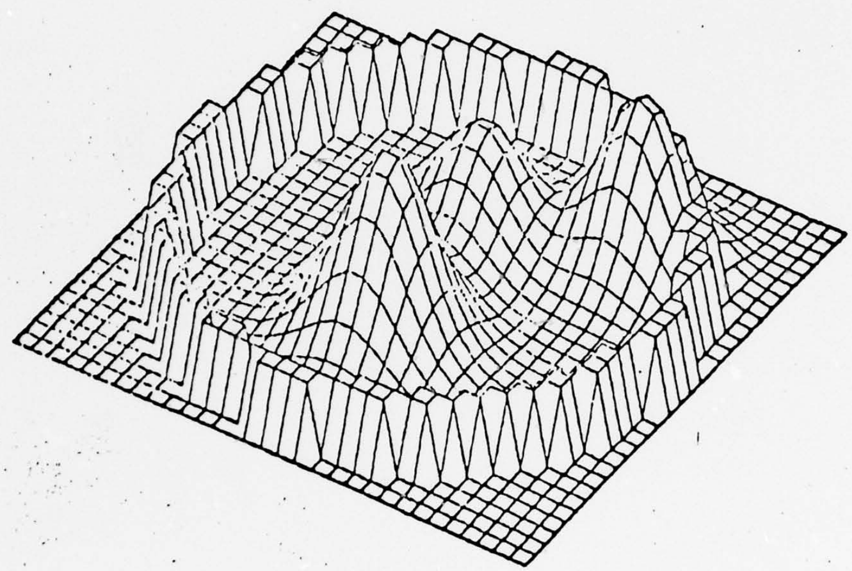


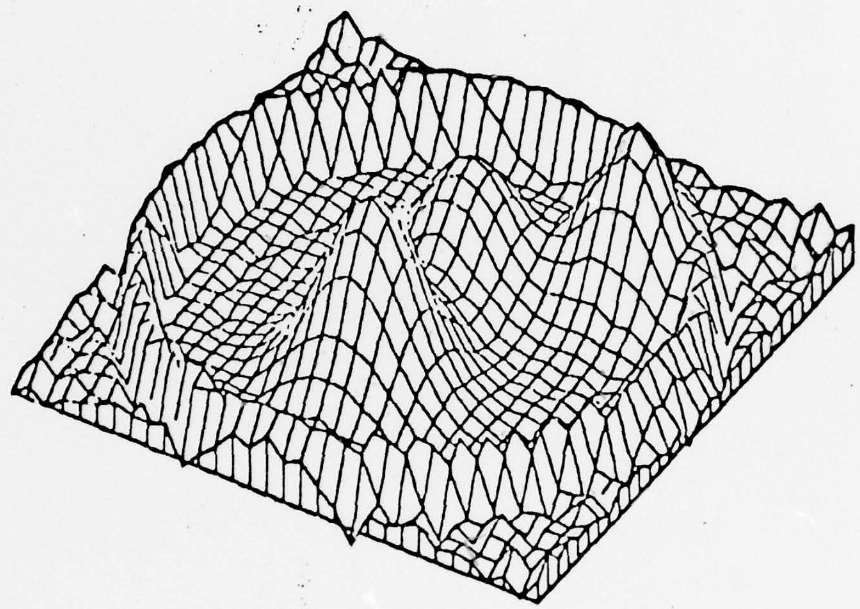
Figure 10



TRUE FUNCTION

Figure 11

SUMMATION OF GAUSSIAN AND CYLINDRICAL DISTRIBUTIONS



20 SCANS FILTERED

Figure 12

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POLLUTION	LASERS	ACCURACY	SENSORS
RADICALS	ALGORITHM	FILTERING	TOMOGRAPHY
TIME-CONTINUOUS			THREE-DIMENSIONAL

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Absorption techniques are being applied to three-dimensional combustion diagnostics. By using multiagular scanning, the traditional "onion-peeling" method can be extended from axisymmetrial flows to arbitrary distributions of radicals and pollutants in the flow. Since Scattering "point" techniques are limited by their very small cross section, such an extension would be a step improvement in sensitivity, down to low radical concentrations. Convolution Fourier transforms and iterative algorithms have already been proven in X-Ray absorption tomography and interferometric application. They are currently tested and comparec and

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radical concentration as they appear in flames or exhausts. The effect of the number of scans (viewing angle limitation), of the instrument noise are analyzed for parallel beams. The results show that a trade-off exists between accuracy and the number of viewing angles. A five-angle procedure gives 10% accuracy with a moderately filtered convolution algorithm. An experiment feasibility study shows that time-continuous three-dimensional mapes of low concentrations (1 ppm) can be obtained up to 20 KHz.